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DISPERSION-STRENGTHENED METAL FIN STRUCTURAL TEST

MURRAY N. ENGLAND

TECHNICAL REPORT AFFDL–TR–74–36

MAY 1974

AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT–PATTERSON AIR FORCE BASE, OHIO 45433

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This technical report has been reviewed and is approved for publication.

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A full scale fin constructed of Dispersion-Strengthened Metal (DSM) material (Ni-$20Cr$-$2ThO_2$) representative of the fin on the FDL-5A re-entry vehicle was subjected to fifty simulated missions of earth orbital ascents and re-entry. The fin structure had a projected area of 15.7 square feet and was loaded and heated to a maximum temperature of 2200°F during the re-entry simulation. This report describes the test setup, procedures and equipment used during the simulation. The fin successfully completed the fifty missions, suffering only local failures which were repaired.

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FOREWORD

This report was prepared by the Experimental Branch, Structures Division of the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. It is a formal record of the tests performed on the DSM Fin, designed and manufactured by the McDonnell Douglas Astronautics, Huntington Beach, California, under Air Force Contract F33615-67-C-1319. Dispersion-Strengthened Metal Structural Development was under the direction of Mr. Charles Ramsey, Advanced Structures Branch, Structures Division, Air Force Flight Dynamics Laboratory.

This report covers tests conducted between December 1970 and September 1972 with Mr. Murray N. England as Project Test Engineer, Mr. Edwin M. Candler as Instrumentation Engineer, Mr. Ronald E. McQuown as Heat Control Engineer, Mr. James H. Specht as Load Control Engineer and Mr. David Huber as Electrical Engineer.

This report complements the final report McDonnell-Douglas has issued as AFFDL TR 68-130, Part II, "Dispersion-Strengthened Metal Structural Development," covering design fabrication and structural test results of the DSM Fin.

ABSTRACT

A full scale fin constructed of Dispersion-Strengthened Metal (DSM) material (Ni-20Cr-2ThO_2) representative of the fin on the FDL-5A re-entry vehicle was subjected to fifty simulated missions of earth orbital ascents and re-entry. The fin structure had a projected area of 15.7 square feet and was loaded and heated to a maximum temperature of 2200°F during the re-entry simulation. This report describes the test setup, procedures and equipment used during the simulation. The fin successfully completed the fifty missions, suffering only local failures which were repaired.

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INTRODUCTION

The need for a multi-mission re-entry vehicle necessitates investigations to develop material and design capabilities required for development of such vehicles. Materials which retain good strength at higher temperatures than do superalloys, and yet do not require the oxidation resistant coatings of the refractory materials, appear to offer cost-effective advantages provided their reuse without refurbishment is on the order of 50 or more flights. Dispersion-Strengthened Metals (DSM) are such materials, having good strength and oxidation resistance up to temperatures of 2200° - 2400°F. The DSM alloy $Ni\text{-}20Cr\text{-}2ThO_2$ was selected for structural development and demonstration by AFFDL Structures Division.

This report describes the tests performed on a full-scale vertical fin made from DSM material based on the FDL-5A re-entry vehicle configuration and projected mission requirements.

TEST ARTICLE

The test article was a highly-swept (Λ_{LE} = 70°) low aspect ratio vertical fin of the FDL-5A configuration. The Huntington Beach Division of McDonnell Douglas designed and fabricated the fin under contract to the Advanced Structures Branch of the Structures Division, Air Force Flight Dynamics Laboratory. The fin had a maximum chord of approximately 8-1/2 feet and a span slightly less than four feet. The theoretical projected area of the full size fin was 17.8 square feet.

The fin structural design consisted of a multi-spar internal structure stiffened with ribs and diagonal members. Figure 1 is a photograph of the fin's internal structure. The Fin's external surface was formed by a series of corrugation-stiffened single faced panels with overlapping edges to permit relative expansion between panels and diminish stresses induced by differential temperatures in the structure. Figure 2 is a photograph of the fin's external surface. The fin leading edge and tip closing segments were omitted from the test assembly to provide an open area at the leading edge channel and tip ribs for the attachment of deflection transducers.

The primary material used to fabricate the fin was Ni-20Cr-2ThO_2 sheet metal. Ni-20Cr-2ThO_2 bar and rod were used for fittings, fasteners, and loading rods in areas of maximum temperature. The spars were formed channel sections with bead-stiffened webs. Ribs and diagonals were formed sheet metal with holes which provided passage for instrumentation leads. The internal structure was assembled by riveting.

The surface panels were made of 0.015 inch face sheets and 0.010 inch corrugations joined by spot welding. Each panel was attached with three flush head screws, two of which went into floating anchor-nuts while the third went into a stationary anchor-nut.

DEVELOPMENT TESTS

Ten months prior to receiving the full scale fin, McDonnell Douglas furnished the Experimental Branch several pieces of DSM material instrumented with the same type of strain gages and thermocouples which they planned to use on the fin. These pieces were used to verify the strain gage calibrations, evaluate the strain gage and thermocouple types and installation techniques, and run efficiency tests to determine optimum heater arrangements and thermocouple life expectancy.

a. Strain Gage Calibrations

Axial and rosette strain gages and thermocouples were mounted on a tensile specimen of DSM material. The tensile specimen was mounted vertically in a loading jig with a hydraulic cylinder and load cell. A small infrared heater was fabricated and mounted to heat the specimen uniformly over the instrumented area.

Loads were applied to the specimen at both room and elevated temperatures (up to 500°F) while the strain gages were read. A final test was run where the temperature was raised until the strain gages failed at 700°F. This information was useful during the full scale fin test in assessing the accuracy of strain gages that were heated beyond their normal operating limit of 500°F.

b. Thermocouple Evaluation

Initially the Experimental Branch received two small (4 x 8 inch) specimens cut from a skin panel identical to the panels to be used on the fin. The small panels were instrumented with chromel-alumel thermocouples which were metal-sheathed and ceramic-insulated wires of 30 gage AWG size

(0.010 in. diameter). Both the chromel and alumel wires were packed in magnesium oxide powder inside a 1/16 inch outside diameter Inconel 600 tube. During installation, a short length of Inconel sheath was removed to expose 1-1/2 inches of each thermocouple wire. These were laid parallel to each other and each wire spot welded three times to the test specimen. An expansion loop was formed in each wire near the sheath to allow for differential expansion between the thermocouple wires and the structure.

These specimens were heated in an oven constructed to duplicate the heater assemblies to be used on the fin. Constant voltages were applied to the heater assembly with different lamp spacings and the temperature of the specimen recorded.

It is desirable to have slightly more power available than is required to produce the desired temperature. However, if too much power is available a malfunction calling for full power could overheat the specimen and cause a premature failure. The lamps were in series-parallel which limited the voltage across the lamps to 300 volts. This was done to avoid excessive lamp failures. For this test an effort was made to achieve the desired temperature with 250 volts across the lamps.

The peak temperatures to be applied to the fin ranged from 800°F to 2200°F. The shape of the fin plus the need for heaters overhanging the fin to prevent edge losses suggested the use of a mix of Research Incorporated, water cooled, aluminum Model 1424 reflectors with Lux Therm, air cooled, lamp holders and air cooled ceramic Model P502M Pyrometric reflectors. Some of the control zones to be used during the fin test would use both types of reflectors, with the power to both types of heater assemblies being controlled by one thermocouple.

During tests to determine optimum heater arrangements and thermocouple life expectancy, sample panels began to develop permanent buckles in both directions. Panel buckling caused the thermocouples to short against the Inconel sheath and give a false signal. Steps were taken to correct this by supporting the sheath. It was then noticed that the high temperature runs were eroding the thermocouple wire. A switch to Platinum/Platinum-10 percent Rhodium thermocouples in an Irish Refrasil sheath cured both problems. McDonnell Douglas was instructed to use the Platinum/Platinum-10 percent Rhodium thermocouples in the Refrasil insulation on the fin where the temperature would exceed 1500°F.

Concurrently, testing of surface panels at McDonnell Douglas led to increased stiffening along panel edges and addition of shallow beads in the panel face sheet to provide controlled deformation without permanent set. A larger one square foot panel of this design was received with platinum thermocouples. This panel gave more accurate efficiency test results for optimum heater arrangements and the platinum thermocouples proved satisfactory.

TEST SETUP AND PROCEDURE

A. Test Component

The fin was mounted horizontally in the test jig for the following reasons:

1. To avoid large differences in free convection heat transfer (chimney effect), thus allowing more accurate temperature control.

2. To simplify the task of counter balancing the load linkage and the test article.

3. To simplify the installation of the deflection transducers.

A transition structure with pinned attachment points was provided by McDonnell to attach the fin to the support jig. The transition structure had slotted holes at Spars 1, 5, 6 and 7. Bushings were inserted in the slotted holes for the ascent tests and removed for the re-entry tests. Braces located at Spars 2, 3 and 4 prevented the transition structure from rotating when chordwise loads were applied.

Loads were applied to fittings riveted to Spars 1 thru 7 at the leading edge and at one chordwise location about mid-span on the aft spar (Spar 1). Figure 3 is a sketch of the loading arrangement.

Fittings riveted to the leading edge near each spar were used for counter balancing (up) and for attaching quartz rods for deflection measurements (down).

B. Heat Control

Water cooled, aluminum reflectors (Research Incorporated) with air cooled, lamp holders (Lux Therm) and 6000 watt Bromine cycle infrared heat lamps were used to heat most of the structure. The leading edge was heated with air cooled, ceramic reflectors (Pyrometric) with 6000 watt Bromine cycle

infrared lamps. Figure 4 is a drawing of the reflector assembly.

The surface area was divided into twelve control zones on each side. Figure 5 is a drawing of the control zones. Each zone had a primary and a backup control thermocouple and control could be immediately switched to the backup thermocouple during testing. One time-versus-temperature program was used for the ascent tests and 11 time-versus-temperature programs were used for the re-entry tests. Figures 6 and 7 show the heat and load programs for the ascent and re-entry tests. Only the hottest control zone is shown in Figure 7.

Heat control was maintained by controlling the voltage across the infrared heat lamps. The programmed versus actual temperature was compared ten times per second throughout the test by a G.E. Heat Control Computer (HCC), Model No. 68A8453, operating in the time-temperature mode. The HCC consisted of a hard wired, special purpose, digitally programmed, analog computer time shared by 40 control channels. The HCC provided control signals to the 580 KW ignitron power regulators which, in turn, regulated the power to the heat lamps. Figure 8 is a schematic of the heat and load control system. Figure 9 is a table relating control zone, HCC channel, ignitron number, number of lamps per control zone and power available.

HCC No. 3 was used for both the heat and load program and heat control for the first ten ascent tests. A bearing failure in the HCC No. 3 drum forced the use of HCC No. 2 for heat control and an Information Technology Incorporated Programmer, Model 4901, for the load program for all the rest of the tests. HCC No. 2 can only handle 300 points vs. 1000 for HCC No. 3 so not enough points were available to describe both the heat and load curves with HCC No. 2.

C. Load Control

Load control was maintained by Compudyne Corporation Model 846 Servo Load Controllers. Two servo controllers were used for the ascent tests and one servo controller was used for the re-entry tests. The servo controller compared the desired load from the load program with the actual load sensed by the load cell in series with the hydraulic loading jack and regulated the servo valves, thus supplying the correct amount of hydraulic pressure to the hydraulic loading cylinder to produce the desired load.

D. Shake Down Tests

The first tests conducted were ascent load only to check out the system and compare strains and deflections with the contractor's predicted values. The strains were 20 percent too high and the vertical deflections 100 percent too high. The contractor blamed the excessive strains on false assumptions of jig rigidity in the computer program used for design. The excessive deflections were blamed on jig rotation. Dial indicators were mounted to measure jig deflection which did occur. The jig was stiffened considerably and the deflections came closer to the predicted values.

Ascent heat only tests (300°F all over) were conducted primarily to debug the system. Several problems were uncovered and corrected before proceeding with the heat and load tests.

Prior to conducting the re-entry tests, the re-entry temperature was scaled down to a maximum of 800°F for the first checkout run. Subsequent checkout runs had the maximum temperature scaled down to 1200°F, 1600°F and 2000°F. These tests served to obtain strain information up to the

limit of the strain gages (500°F) and to check out the heating apparatus at higher temperatures.

E. Instrumentation

There were 32 uniaxial strain gages (Micro-Measurements Type WK-09-250BG-350) and 9 biaxial gages for shear measurements (Micro-Measurements Type WK-09-125TD-350). Adjacent to each of the 41 strain gages was a thermocouple so the temperature at the strain gage could be used in conjunction with the apparent strain to compute the thermal and mechanical strains. The internal structure had 16 additional thermocouples. Figure 10 shows the location of the internal instrumentation. Four thermocouples were located on the support frames. The surface panels were instrumented with 59 thermocouples. Forty eight of these were control and back-up thermocouples. Figures 11 and 12 show the location of the surface panel and support frame thermocouples.

McDonnell Douglas installed the strain gages and thermocouples. When the fin arrived at the AFFDL's Experimental Structural Test Facility Branch the thermocouples were inspected and the installations were found deficient. Each thermocouple wire was spot welded three times, but excessive power had been used so most of the wires were burned in two at each spot weld. In addition, excessive cement surrounded the expansion loop, rendering the loop ineffective in relieving the tension on the wire. Figure 13 is a photograph of a typical faulty installation. All of the external and some of the internal thermocouples had to be reinstalled by Experimental Branch technicians before the test could be started.

The fin had tabs riveted to the leading edge beam adjacent to each spar for the measurement of normal deflections. Chordwise deflection of the aft spar at the tip was also measured. Research Incorporated Displacement Transducers Model 4046 were mounted on a separate jig several feet away from the fin. Quartz rods were attached to the fin and extended down about two feet away from the fin at each deflection location to eliminate elongation due to temperature expansion of the wire chain normally used to translate movement to the deflection transducers. During the test six more displacement transducers were added to determine fore and aft deflection and rotation of the transition structure and jig deflection. Figure 14 shows the location of the deflection transducers.

Test data were recorded on the Structures Test Facility High Speed Data Acquisition and Processing System (HSDAPS), which is built around an on-line Control Data Corporation Model 1604B computer. The data system hardware has a high degree of modularity and, in its ultimate configuration, can accept data inputs from 14 analog measurement subsystems (approximately 2,700 low-level analog channels).

Measurement subsystems are assigned to various projects on the basis of the number of transducers involved and the sampling rates required. The subsystem selected for the DSM test program was a locally engineered and fabricated signal conditioning unit, designated F11, which is a 256 channel device capable of sampling each data line five times per second. This unit converts measured data in the $\pm$100mv full-scale range to 14-bit bipolar binary digital information. The unit subsequently transmits the

information to the CDC 1604B computer and to a backup "off-line" magnetic tape system.

The function of the CDC 1604B computer in the real-time test environment was to:

1. Format check all incoming data.

2. Write raw data on magnetic tape for post-test processing.

3. Perform real-time analysis of measured data and present the results on:

a. The Computer Analyzed Data Display of Indicated Error (CADDIE) alarm monitor subsystem which indicates temperature limit conditions

b. An alphanumeric video display terminal which presents selected data in tabular form

c. A full graphic/alphanumeric subsystem which presents specimen response data in annotated graphical form for on-line evaluation

4. Optionally perform analysis for automatic test termination to preclude catastrophic failure.

In the post-test environment, the computer was used to complete analysis of all data, output hard-copy tabular data on the system printer, and prepare plotter tapes for an off-line CalComp plotting system.

F. Safety Considerations

Safety of the test personnel and the test specimen was an important consideration in the design of the test setup and the selection of the test procedures.

Two closed circuit television cameras were used; one to view the test specimen and the other to view the test personnel on the test floor.

The test director was in constant phone communication with the test personnel on the test floor, the instrumentation engineer at the HSDAPS console and the electrician in the ignitron room. Manual abort buttons were available on the test floor as well as the control room. The test director normally was the person to decide when to abort the test, but in case of emergency the floor engineer could abort the test.

The test director had the capability of reading the actual temperature, the programmed temperature, the power and the Δe (error signal) of any control zone using the HCC scanner at any time during the test. The instrumentation engineer could supply the actual temperature of the backup thermocouple and any data thermocouples.

The data and backup thermocouples were monitored by the data computer and displayed on the CADDIE. The CADDIE consisted of two boards cut to the shape of the fin and marked off into control zones with three small light bulbs for each control and each backup thermocouple. A yellow light bulb came on if the temperature was 50°F over the program, a red light if 100°F over, and a green light if 100°F under the program. If the temperature exceeded the program by 200°F for two successive data samples, the computer automatically aborted the test. The data sample rate varied between one sample every two seconds and one sample every ten seconds. All of the control and backup thermocouples and 16 data thermocouples were tied into the automatic abort.

Each channel of the heat rate computer had lights to indicate if it was working properly. Visicorder (Honeywell Model 1612) traces of Δe, power and temperature were continually monitored during the test.

The load controller error was set to ± 5 percent to dump the load either on overload or if the loading rate was too fast or too slow. A monitor located on the test floor where the load control equipment was located showed the load engineer the load the High Speed Data Acquisition and Processing System was recording from the other bridge of the load cell.

The deflection transducer control modules, Compudyne Corporation Model 4095, were set to dump the load if a deflection exceeded the preset limits by 10 percent.

Prior to the start of each test the ANGJQ-9 Programmer Comparator (a tape controlled automatic checkout system) was used to assure the Heat Control Computer switch positions were properly set.

A light panel board, located on the test floor, consisted of a board in the shape of the fin's planform marked off into control zones. A light bulb was located in each zone and the illumination intensity of each bulb was proportional to the power being applied to that zone. The light panel board was constructed to aid the floor electrician in determining whether power was lost to a control zone. During peak heating the heat lamps are extremely brilliant and it is difficult to determine which heat lamps are not functioning.

A 36 step checklist was followed each time a test run was made to assure everything was ready and each piece of equipment activated in the proper sequence.

TEST RESULTS

The DSM fin sustained the 50 ascent and 50 re-entry cycles of heat and load with only non-catastrophic local failures which were repaired. These were observed after the fin had gone through 20 ascent and 16 re-entry cycles.

The inspection following Re-entry 16 revealed a buckle in the leading edge channel at the upper splice position near Spar 3. Also, failed rivets were evident at both upper and lower leading edge splice locations. Figure 15 is a photograph of the buckled channel and some of the failed rivets. The panels were removed and eleven more rivet failures discovered. An angle doubler .040 x .6 x .75 inside the channel splice had also failed. The failed parts were removed by McDonnell Douglas for metallurgical examination.

McDonnell Douglas designed the repairs and sent personnel to the Experimental Branch to install them. The splice joints at Spar 3 and Spar 5 (lower splice) were reinforced by internal and external doublers (Figures 16 and 17 show the repair doublers installed). In all, 280 rivets were used in the repair and included replacement of failed or suspected rivets near the leading edge of the internal structure. The rivets were replaced with the next larger size rivet. One panel attach fitting was replaced by McDonnell Douglas which became necessary when an attachment screw failed during removal of surface panels.

While replacing instrumentation damaged during the repair, an Experimental Branch technician discovered another cracked angle which was probably cracked during the repair of the fin. This part was a shear clip connecting the webs of the upper rib, a diagonal channel and Spar 2.

McDonnell Douglas provided a replacement angle and Experimental Branch personnel installed it. Five months of testing were lost making these repairs.

An analysis of the data along with a metallurgical examination of the failed parts was conducted to determine the sequence and cause of the failures. This analysis is discussed in detail in "Dispersion-Strengthened Metal Development", AFFDL TR 68-130, Part II, prepared by McDonnell Douglas Astronautics Company. The analysis indicated the failures, probably initiated prior to Re-entry 16, were progressive in nature and were not caused by oxidation. An independent analysis of the data by Experimental Branch personnel supports McDonnell Douglas' contention.

Re-entry 17 was aborted after 1060 seconds when an overtemperature thermocouple triggered the CDC 1604B dump. A buckle was found in the leading edge between the reinforcement doublers. An investigation revealed that the transition structure to jig bolts were much tighter than the required "finger tight". This restrained the specimen sufficiently to cause the leading edge channel to buckle under compressive overload. This thermal growth restriction also helped explain the local failures along the leading edge following Re-entry Test 16. The buckle was not repaired and the balance of 50 ascent and 50 re-entry tests were conducted with no further damage to the fin. Figure 18 is a photograph of the buckle.

The fin was returned to McDonnell Douglas where an extensive post-test metallurgical examination was conducted on the structure. The results are published in AFFDL TR 68-130, Part III, "Dispersion Metal Structural Development".

A copy of all the test data will be kept on file at AFFDL/FBT.

CONCLUSIONS

1. The Ni-20Cr-2ThO_2 vertical fin was capable of sustaining 50 ascent and 50 re-entry heat and load cycles with no significant degradation. Thus, a reuse capability was demonstrated for this uncoated metallic system where temperatures repeatedly reach 2200°F.

2. Structural tests of the fin indicated no major shortcoming in the design approach utilized. Local failures were sustained without causing general failure of the structure. That the design concept allowed for thermal growth and movement of the structure to minimize failure due to excessive thermal stresses was evident in the measured deflections.

3. It was demonstrated that repairs could be made with ordinary shop tools and the fin restored to its original strength.

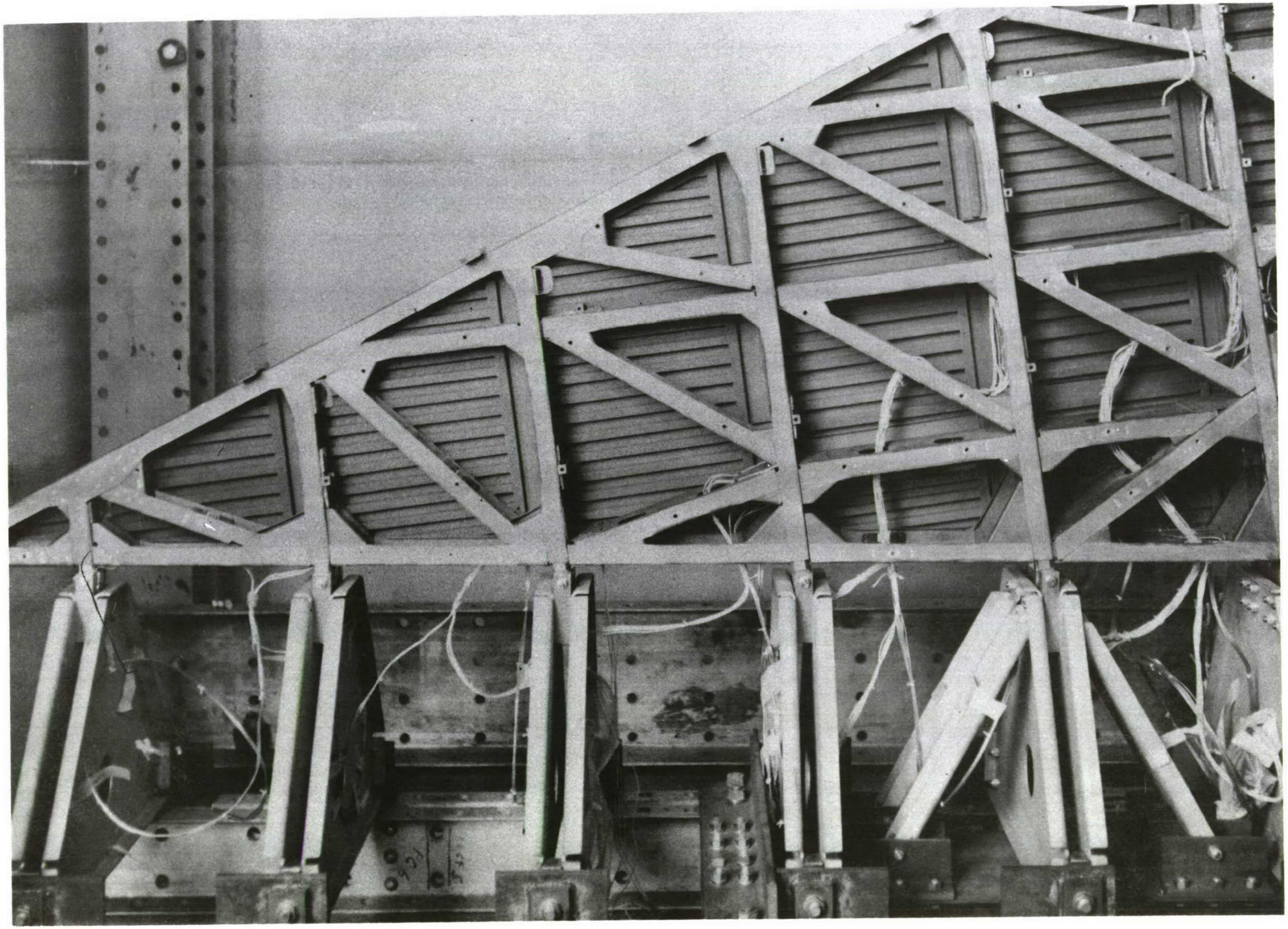

Figure 1. Fin Internal Structure Mounted on Transition Structure

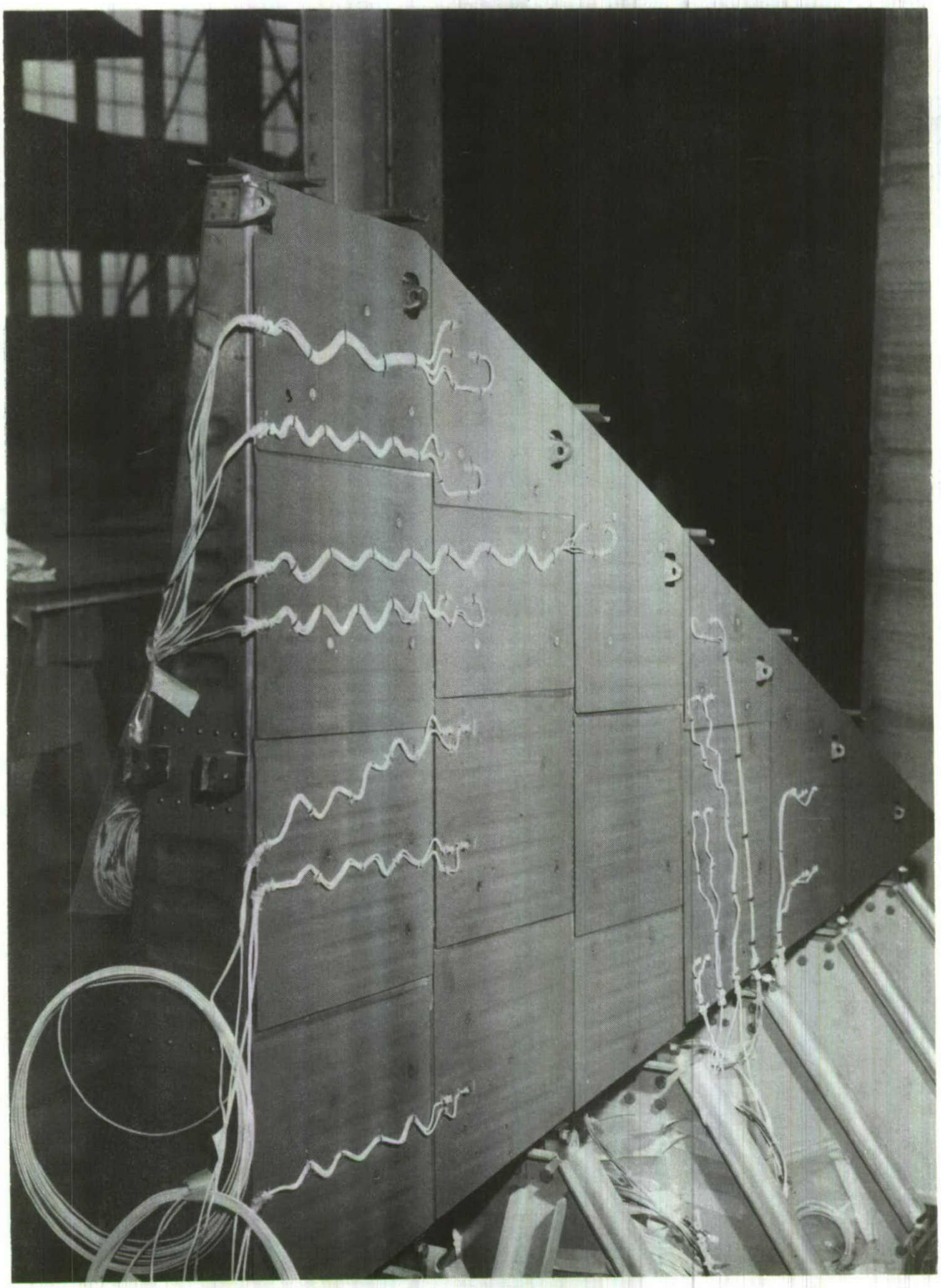

Figure 2. Fin Panels Showing Thermocouple Installations

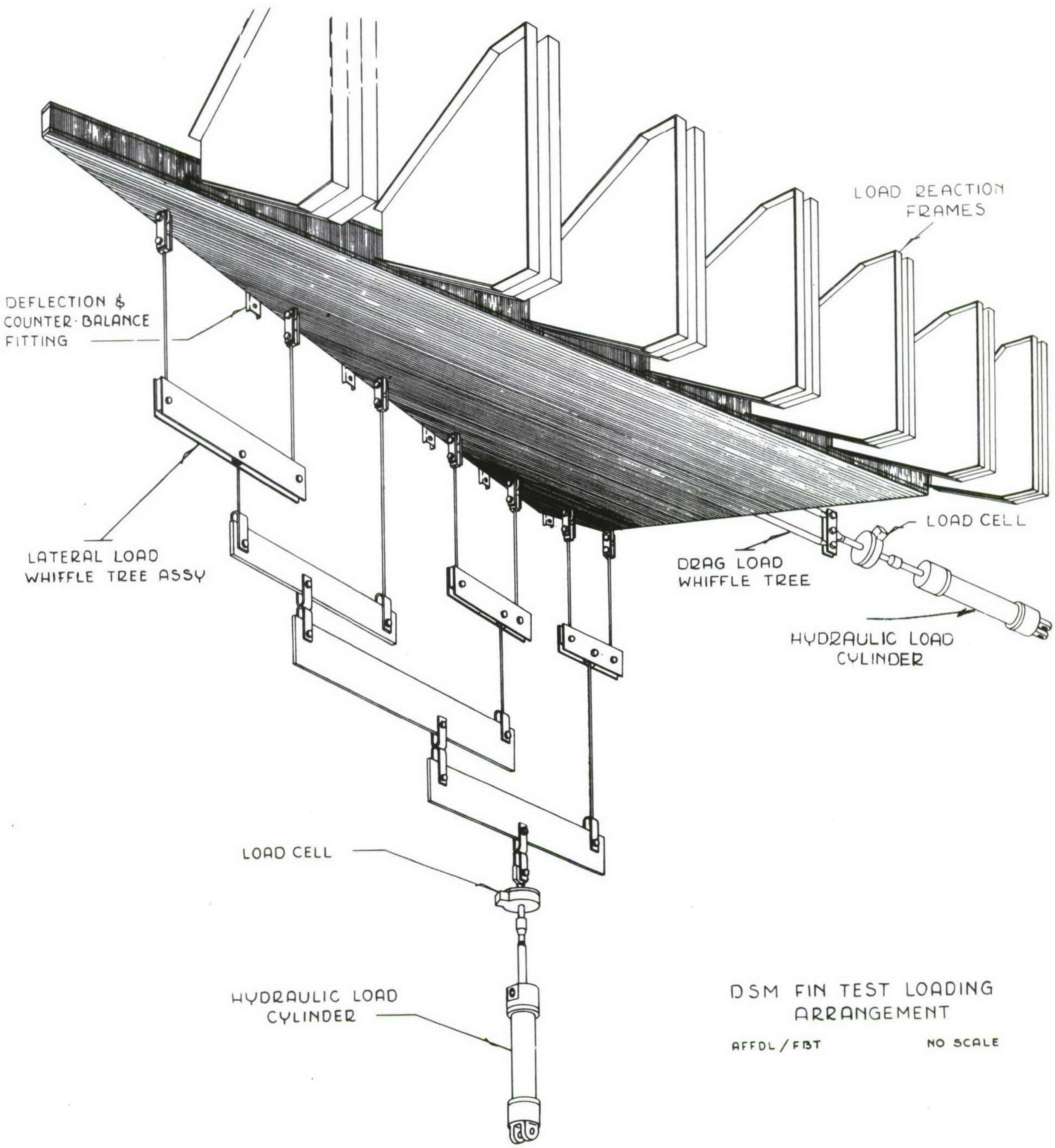

Figure 3. Fin Test Loading Arrangement

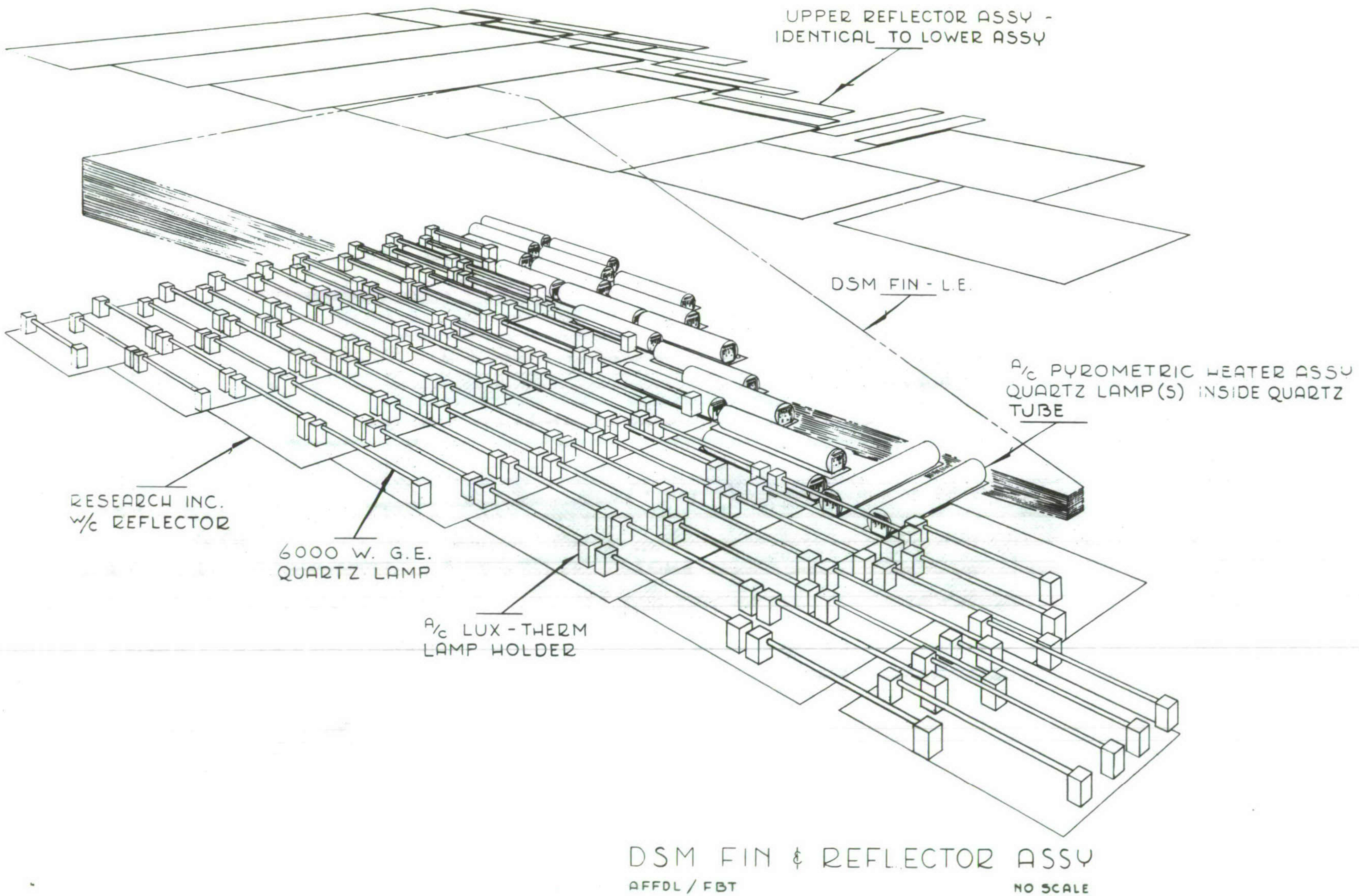

Figure 4. Reflector Assemblies

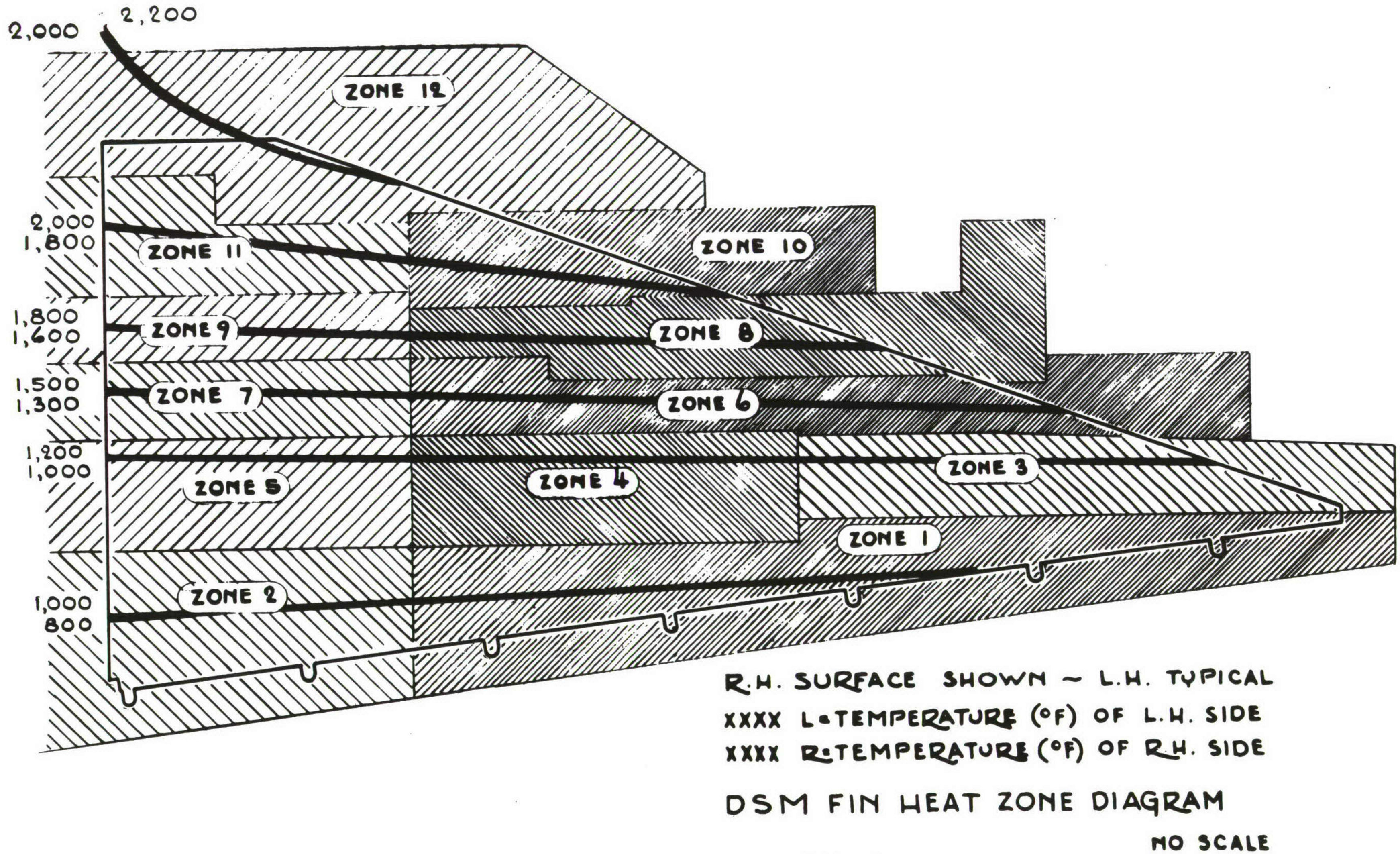

Figure 5. Heat Zones and Isotherms

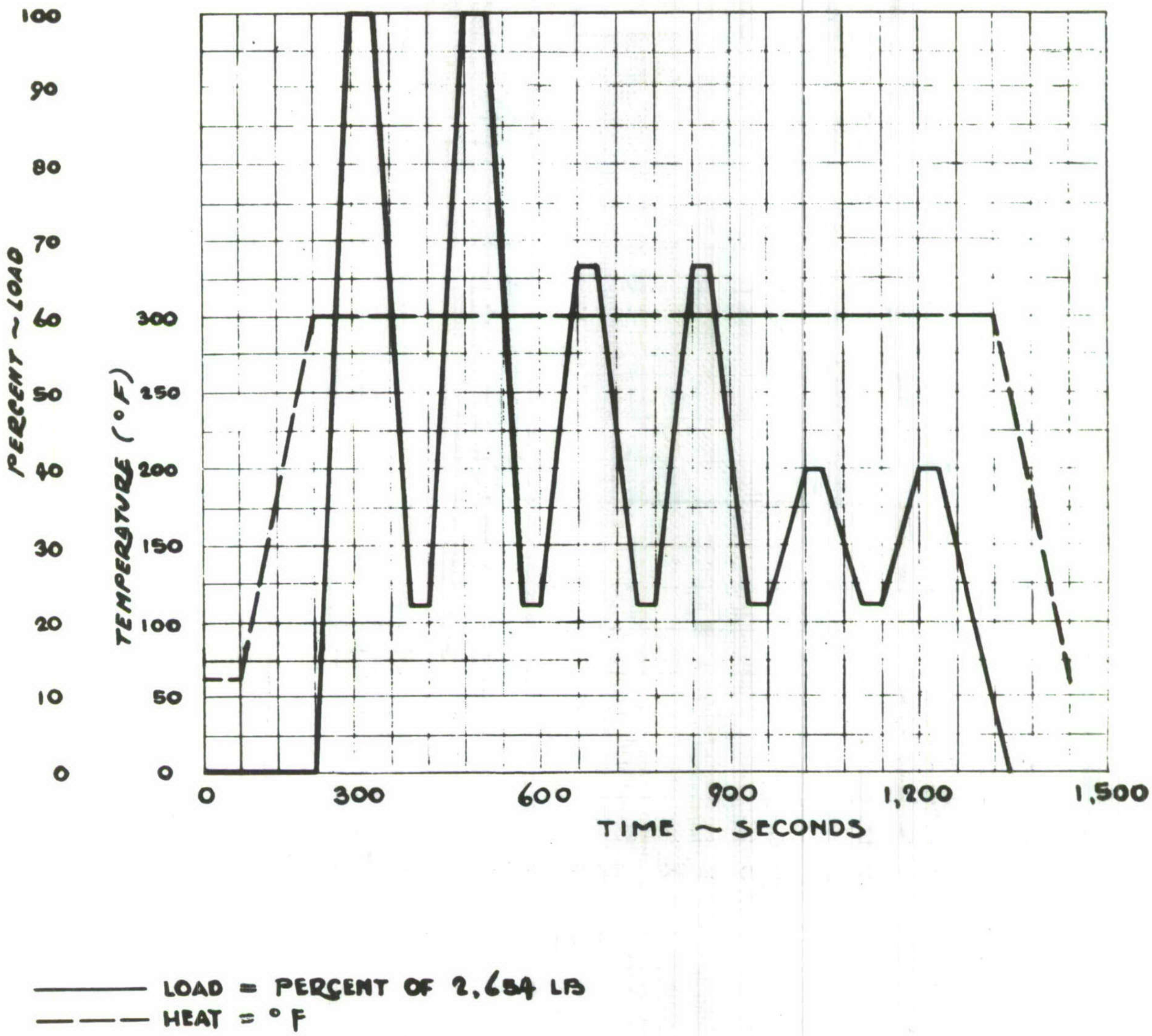

Figure 6. Ascent Heat and Load Profiles

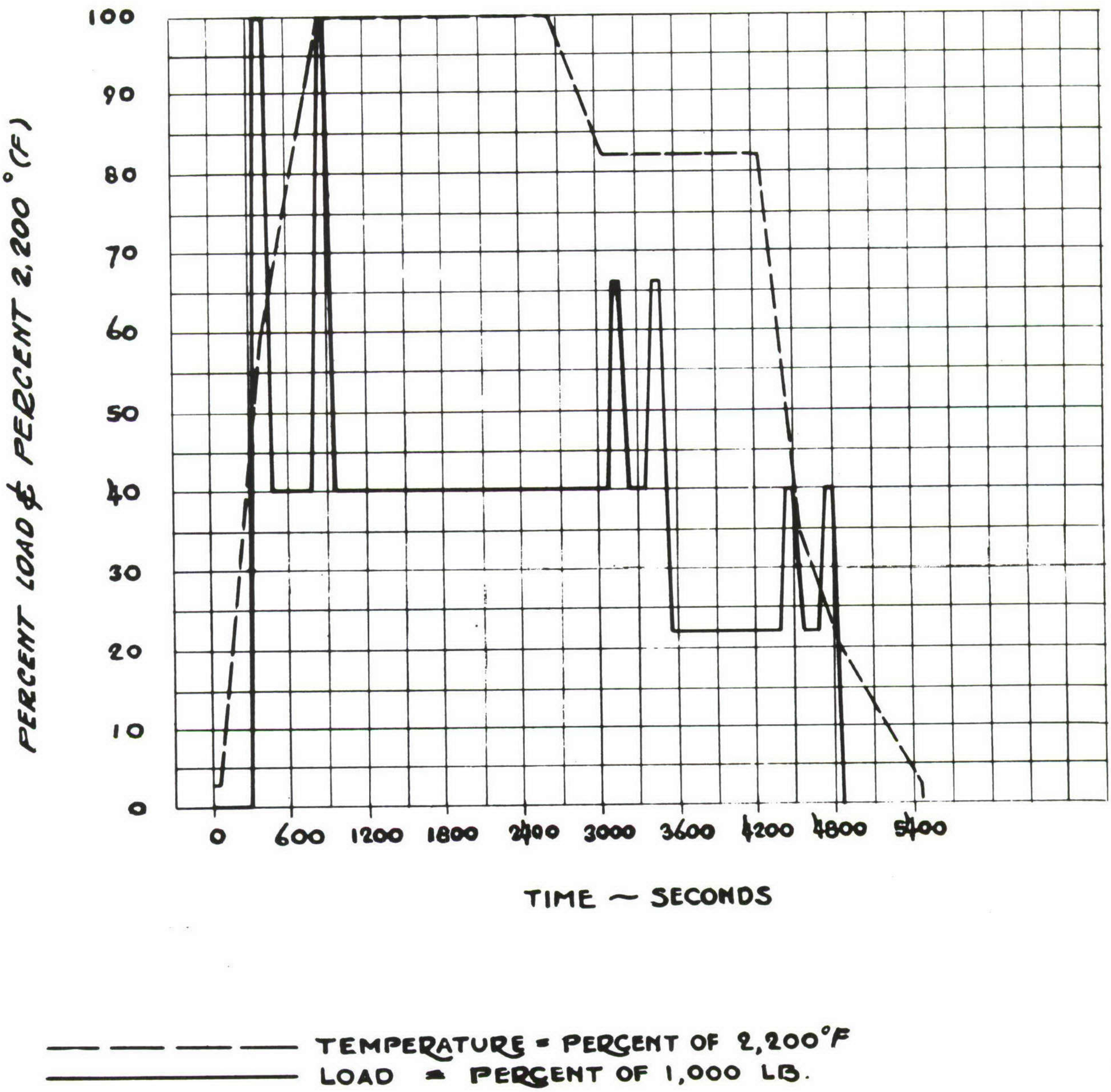

Figure 7. Re-entry Heat and Load Profiles

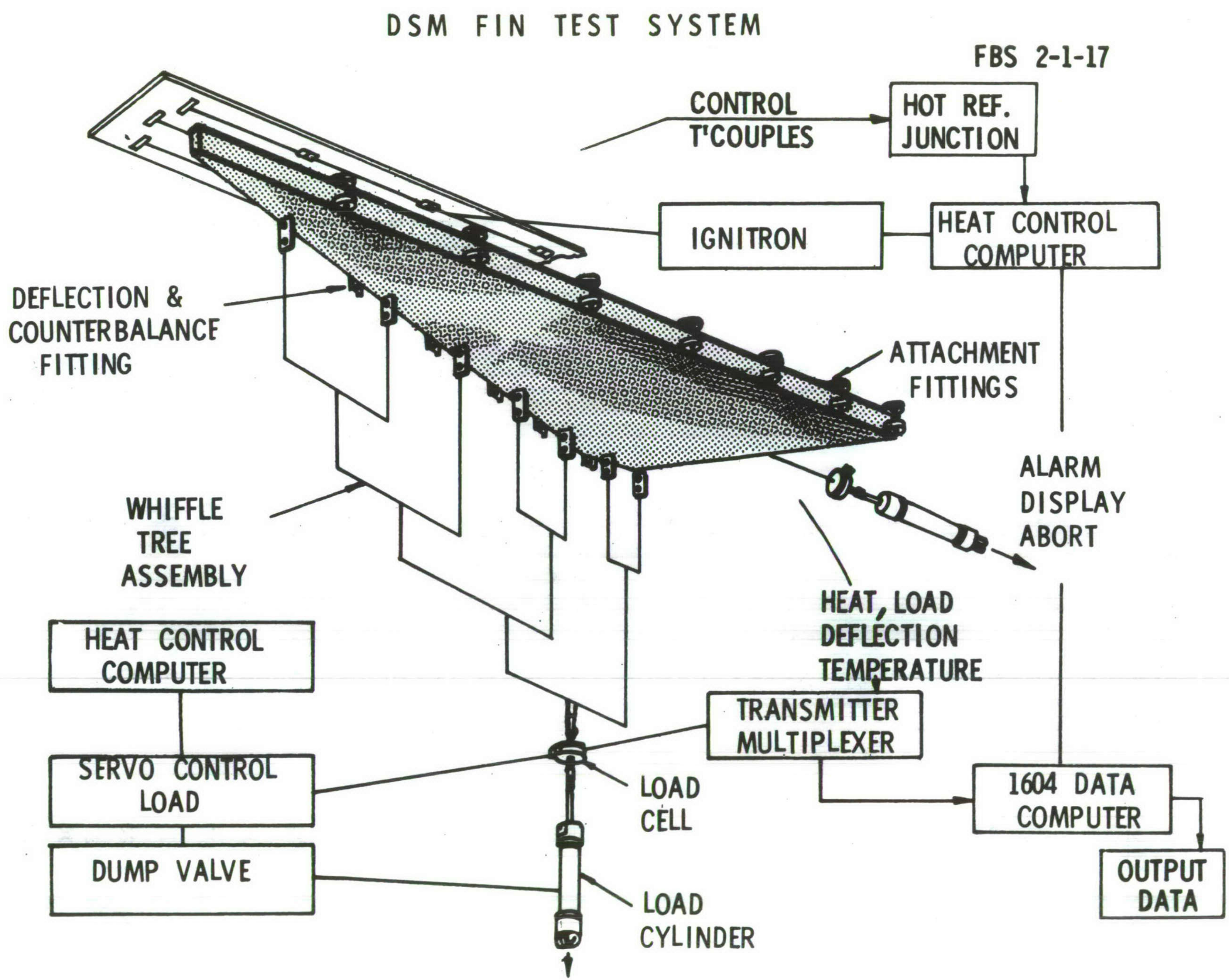

Figure 8. Heat Load and Data Systems

DSM FIN

ZONE	CHANNEL	IGNITRON CHANNEL	PRIMARY T/C	BACKUP T/C	NUMBER OF LAMPS	KW AVAILABLE
			TOP			
1	6	16	101	102	16	48
2	7	17	105	106	10	30
3	8	18	107	108	8	24
4	9	19	109	110	6	18
5	10	21	111	112	6	18
6	11	22	113	114	12	36
7	12	23	115	116	8	24
8	13	24	117	118	18	54
9	14	25	119	120	8	24
10	15	26	121	122	14	42
11	16	14	123	124	12	36
12	17	15	125	126	40	120
			BOTTOM			
1	18	33	201	202	16	48
2	19	34	205	206	10	30
3	20	35	207	208	8	24
4	21	36	209	210	6	18
5	22	41	211	212	6	18
6	23	42	213	214	12	36
7	24	43	215	216	8	24
8	25	44	217	218	18	54
9	26	45	219	220	8	24
10	27	46	221	222	14	42
11	30	47	223	224	12	36
12	29	48	225	226	40	120

Figure 9. Table Relating Control Zone, HCC Channel, Ignitron, Number of Lamps, and Power Available

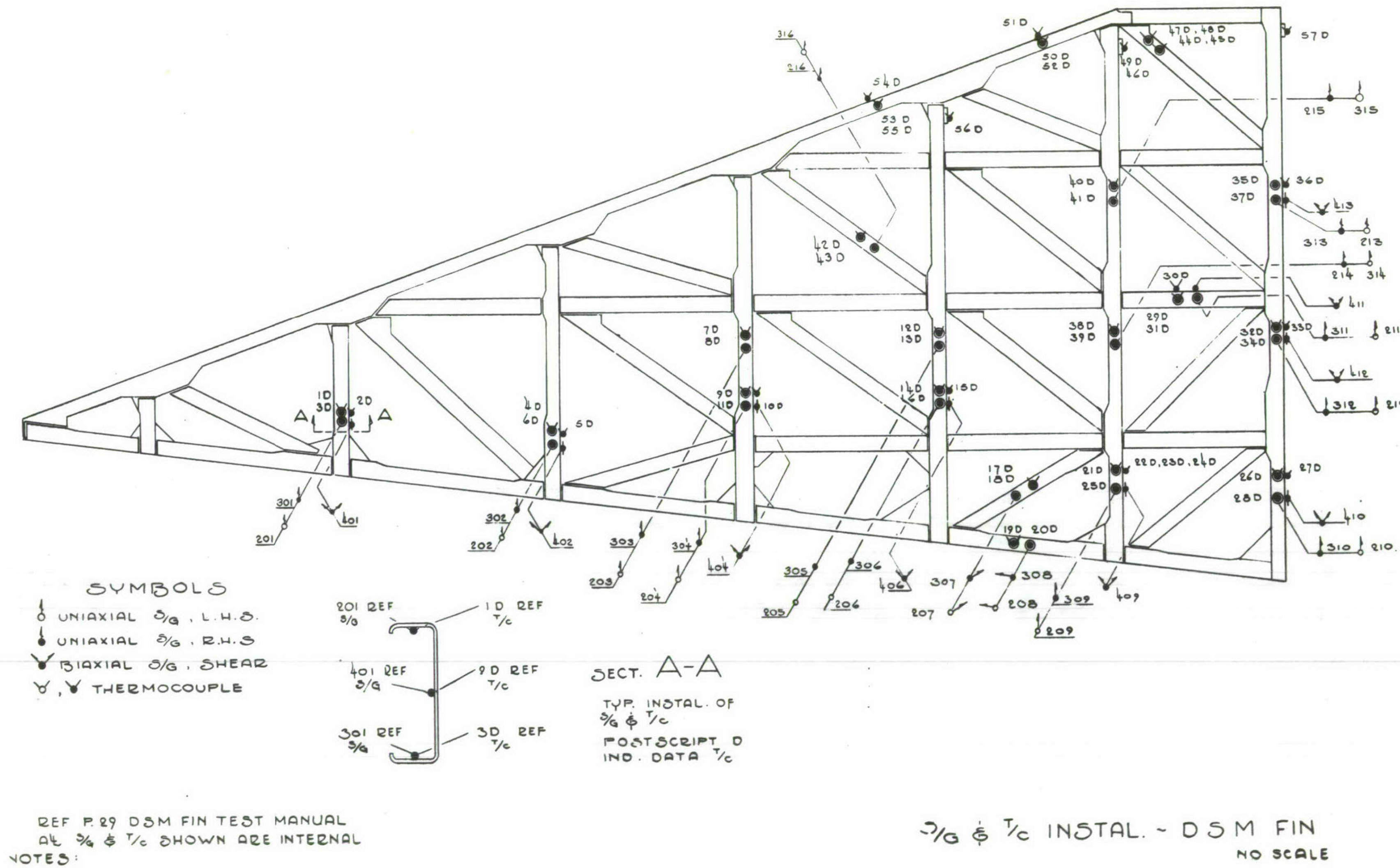

Figure 10. Location of Internal S.G. & T.C.

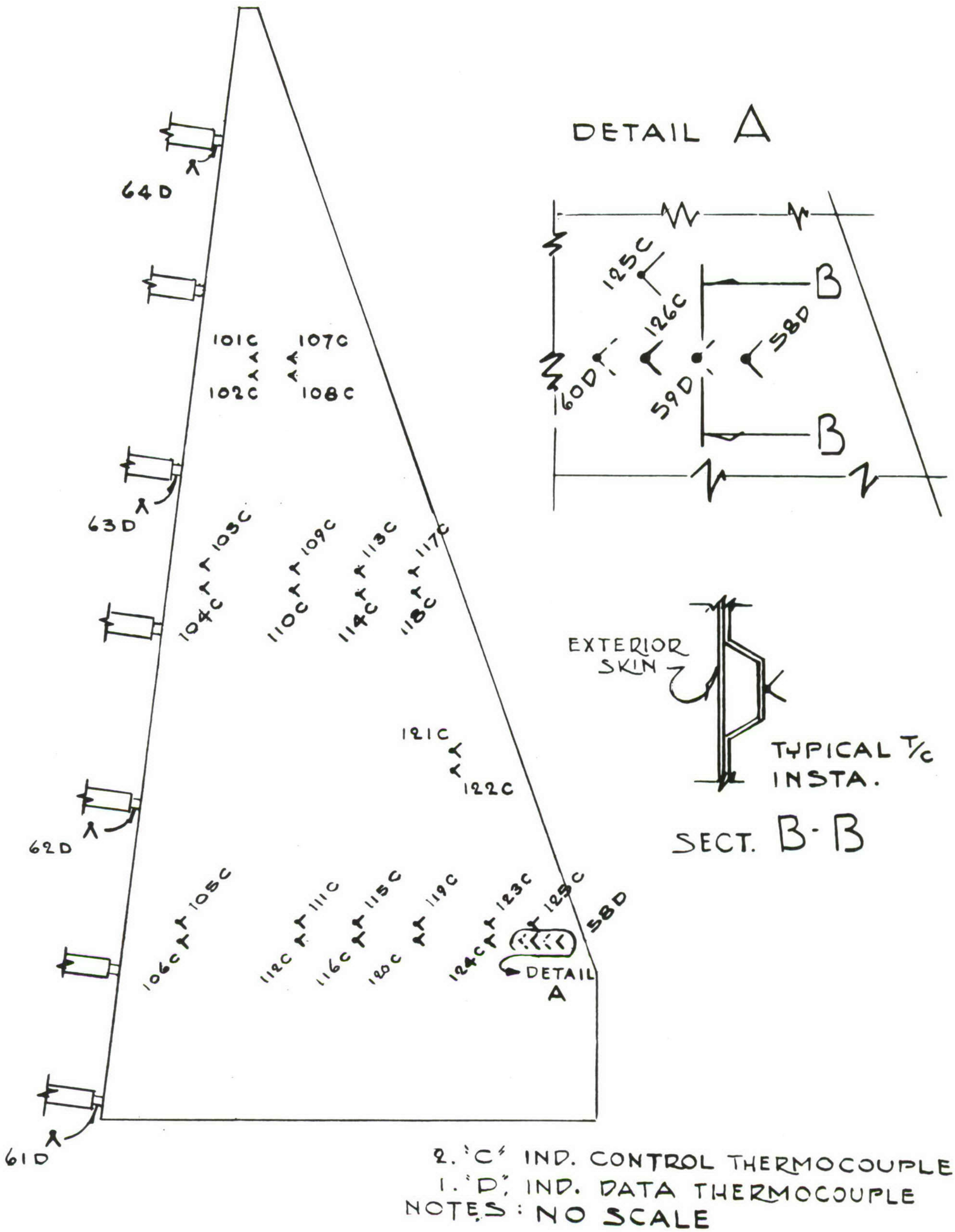

Figure 11. Surface Panel and Support Frame Thermocouple Locations (L.H. Side)

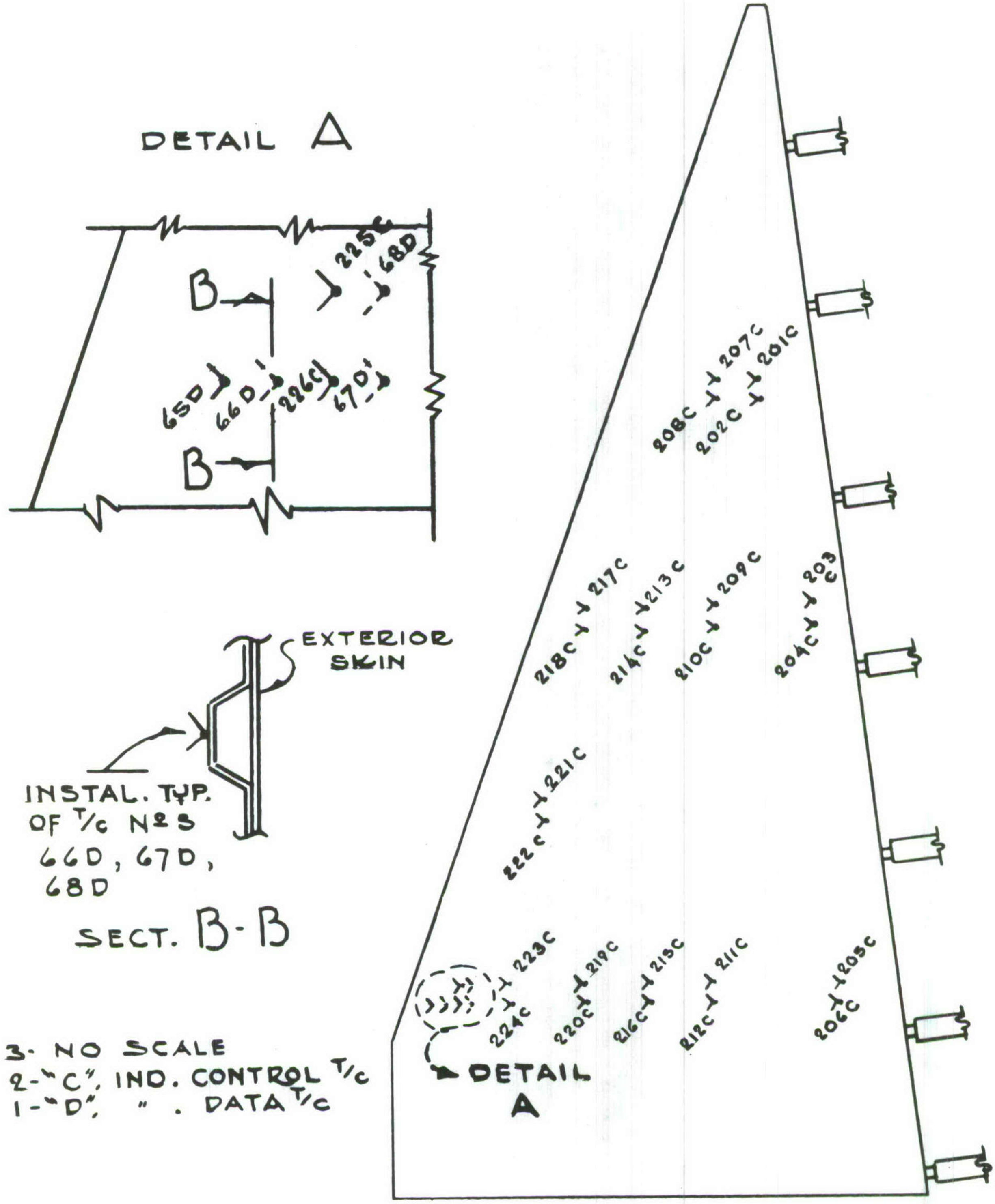

Figure 12. Surface Panel Thermocouple Locations

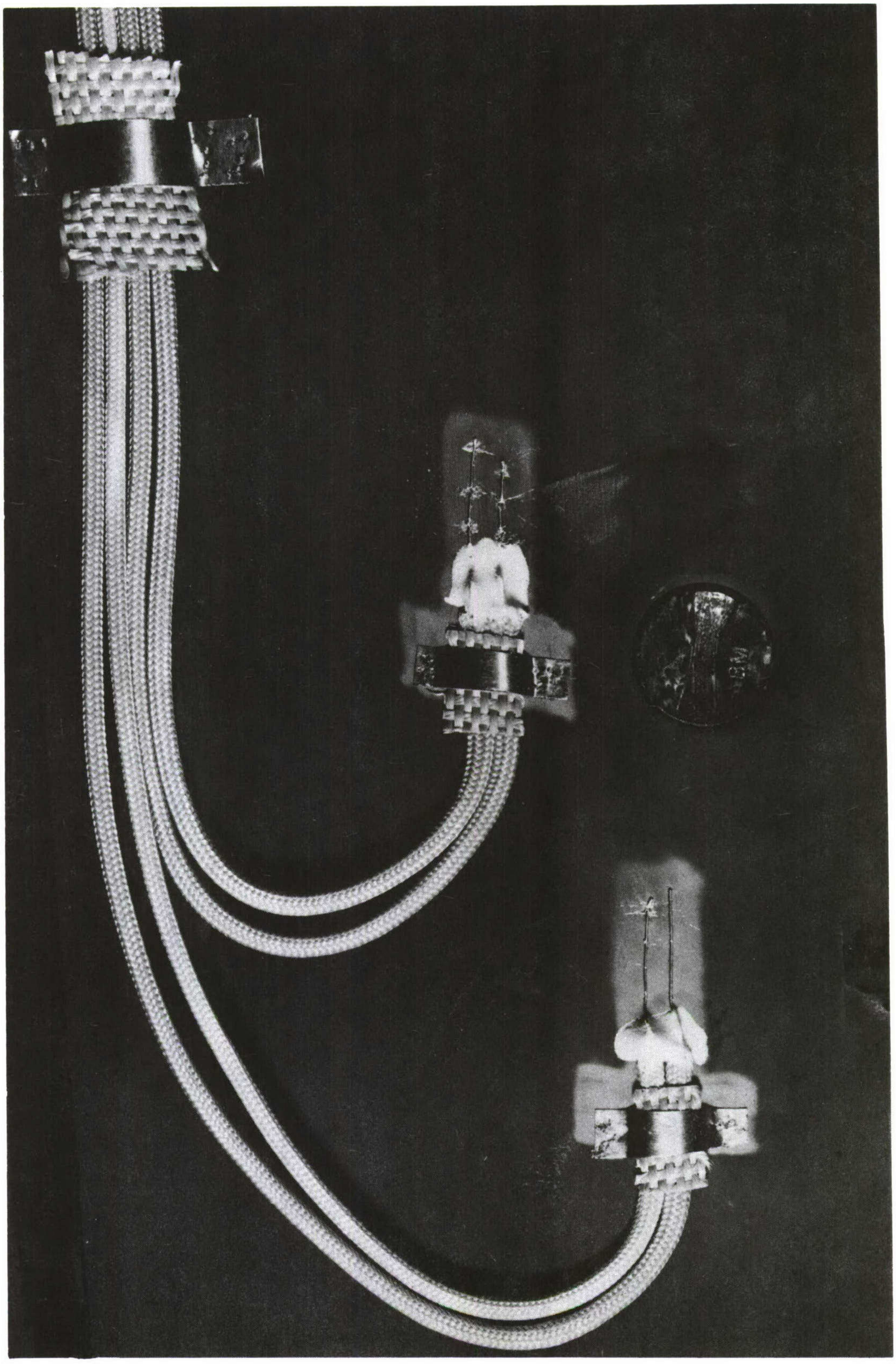

Figure 13. Bad Thermocouple Installations

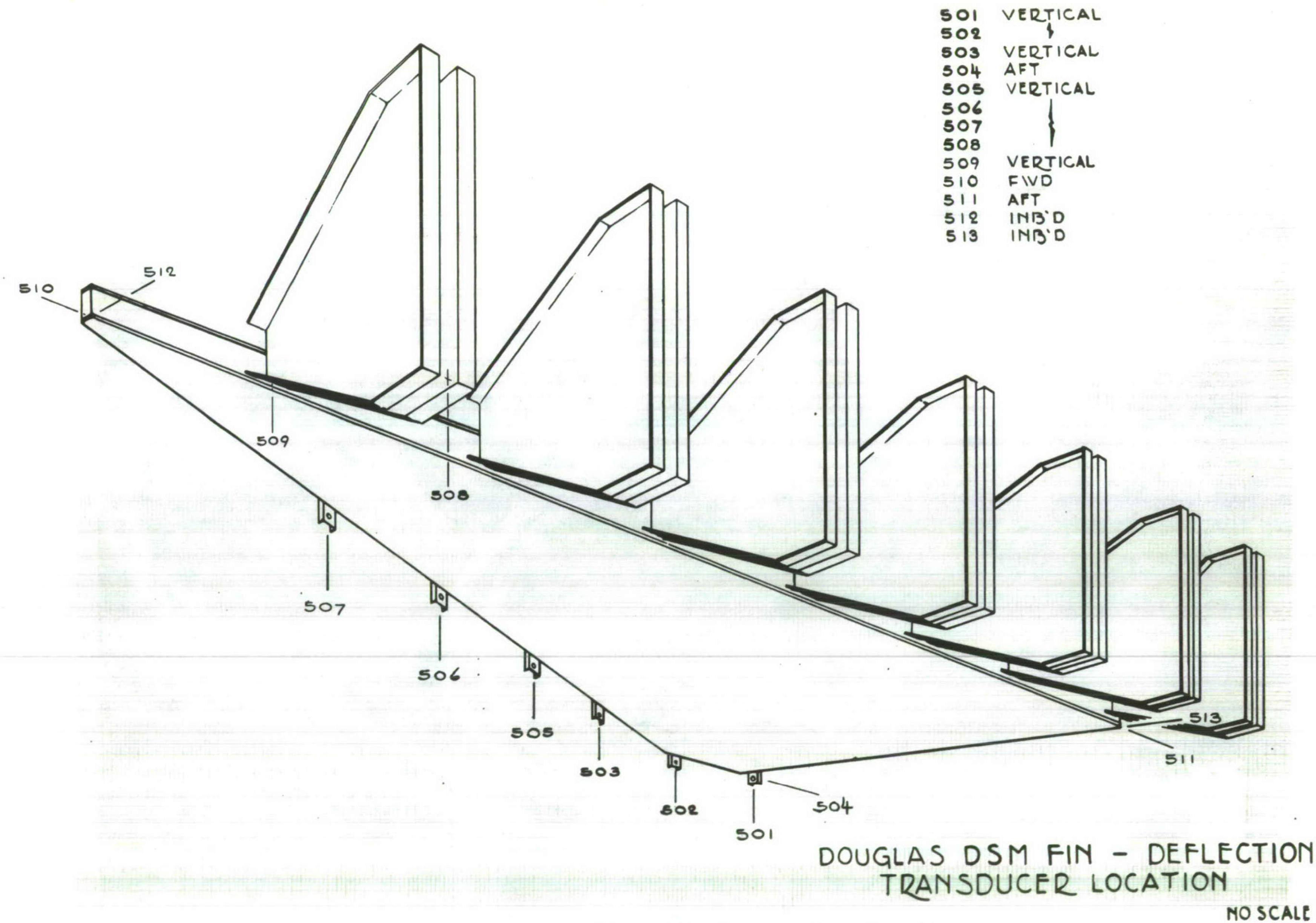

Figure 14. Deflection Transducer Locations

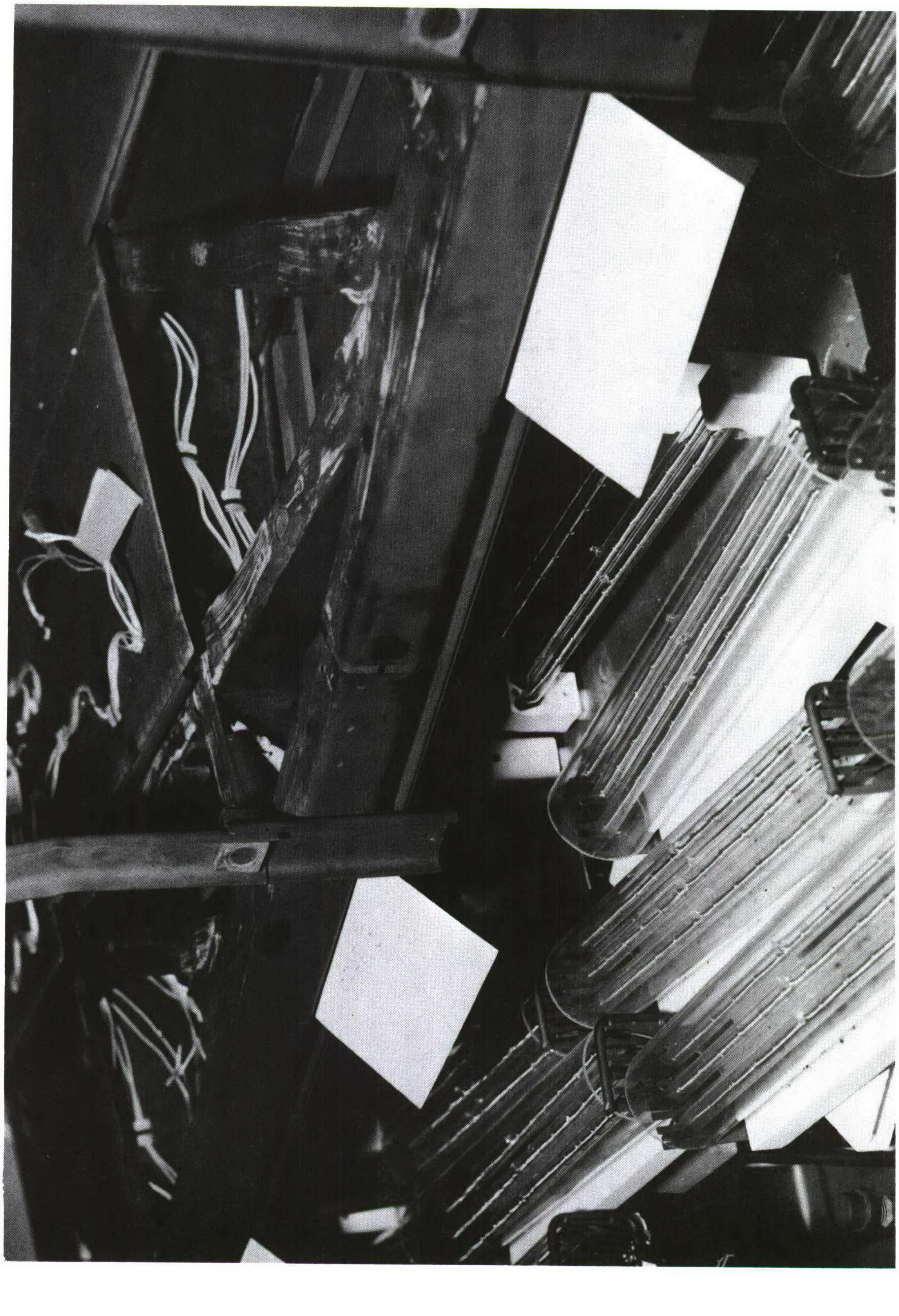

Figure 15. Re-entry 16 Buckled Doubler

Figure 16. Spar 3 Repair Doubler

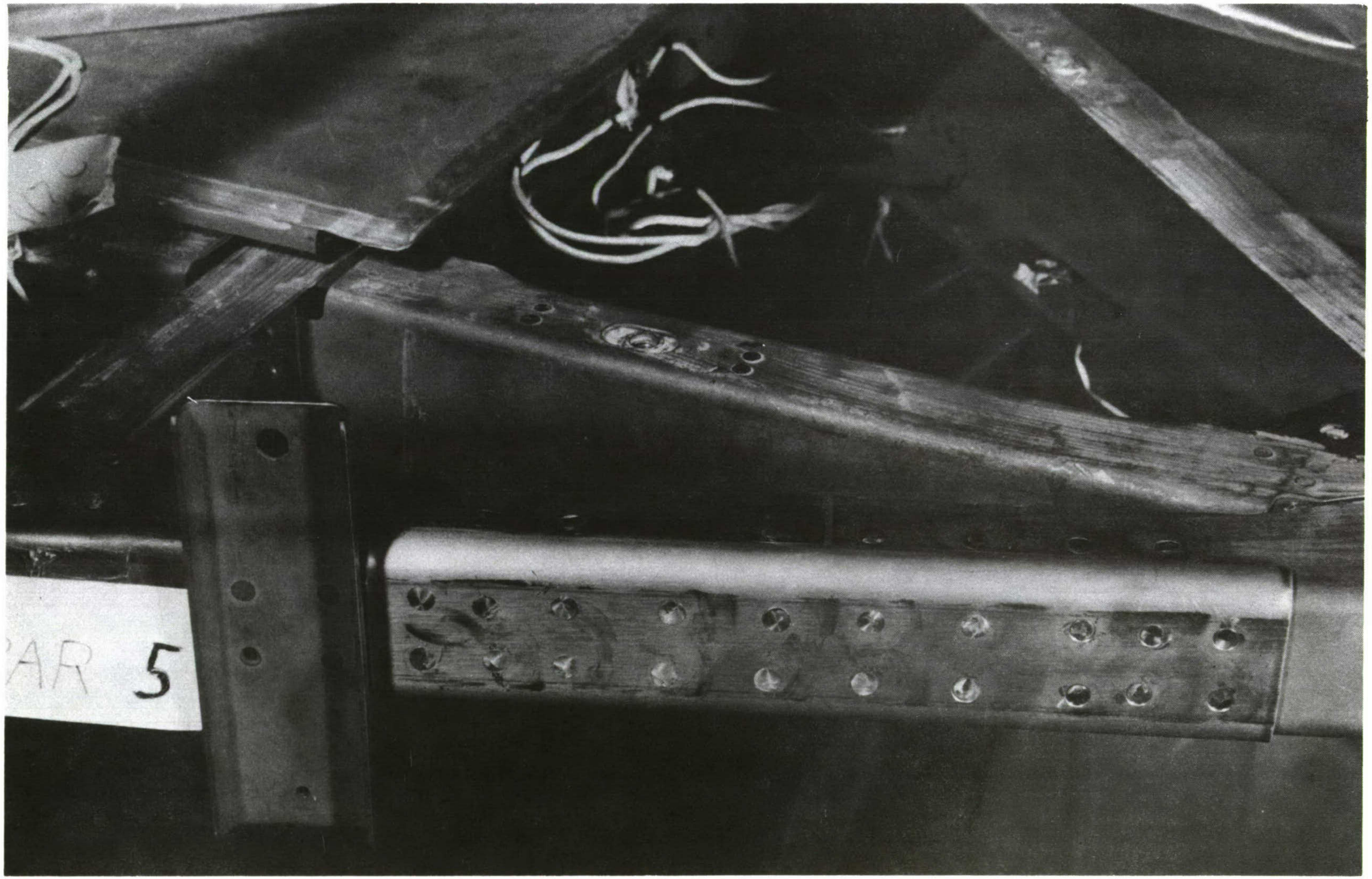

Figure 17. Spar 5 Repair Doubler

Figure 18. Reentry 17 Buckle in Leading Edge Beam

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